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Flame-vortex interactions

The interaction of an isolated vortex with a laminar flame is the "building block" in any model of turbulence-chemistry interactions because it introduces the effects of strain, curvature and unsteadiness. Quang-Viet Nguyen and Phillip Paul are investigating such flows using planar laser-induced fluorescence imaging.

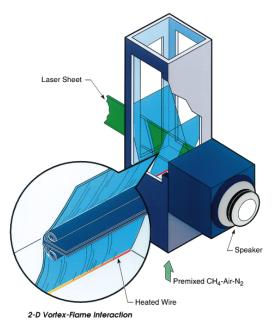


Figure 1: Schematic of the V-flame flow facility.

Figure 1 shows a schematic of the flow facility which consists of a laminar V-flame burner, a vortex generator and a test section fitted with quartz windows. A two-dimensional linevortex pair is generated by applying an impulse to the speaker in the vortex generator. This flow system produces highly reproducible conditions which means that the time evolution of the flame vortex interaction can be recorded by taking a series of images as a function of time delay between firing the speaker and firing the lasers.

Figure 2 shows two sets of corresponding PLIF images of OH and CH taken in a slightly fuel rich methaneair flame. In Figure 2 the reactants are on the right and the products on the left. The flame front is a diagonal punctuated by a half circle that cuts across the images. This half circle contains the vortex pair on the reactant side. The OH images represent the distribution of a long-lived product of combustion. The CH images represent the distribution of a short-lived intermediate that can be interpreted as the primary flame front itself. The lower and upper pairs of images in Figure 2 show the condition just before and after the vortex-induced breakage of the CH surface. There is a 4 to 5 fold increase in OH concentration in response to this break. In a stoichiometric mixture the OH field appears to be unaffected by breakage of the CH surface.

In this study the full time evolution of the flame-vortex interaction for a range of stoichiometries and several fuels (methane, propane and methanol) has been recorded. There are a number of features in common which appear to challenge the basis of many models of the process: First, the CH surface does not break like a balloon, rather it fades away over several milliseconds. Second, once the CH surface breaks we do not find any CH produced in the postflame gases associated with the burnout of the vortex core. Third, it takes some 20 ms for the CH surface to reconnect and this action appears to require the return of the OH field. Finally, the large increase in OH associated with breakage of the CH surface appears for each fuel under stoichiometric to rich conditions.

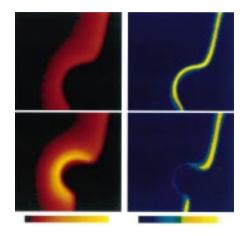


Figure 2: PLIF images of OH (left) and CH (right). The image field is 2 x 2 cm. The lower row is taken 2 ms after the upper row.

This flow geometry was designed in direct collaboration with Habib Najm and Jackie Chen to enable direct comparisons between experiment and the results of full chemistry and comprehensive fluid dynamics simulations of the event.

The Central States Section of The Combustion Institute recently awarded its 1996 Best Paper Award to Dennis Siebers for "Autoignition of Hydrogen Under Direct-Injection Compression-Ignition Engine Conditions." The paper was selected from 150 submissions to the 1995 joint meeting of the Central States/Western States/Mexican National Sections of the Combustion Institute and American Flame Research Committee. (See *CRF News*, 17:5 for a related article.)

Model developed to predict burnout during pulverized coal combustion

Melissa Lunden and Robert Hurt (Brown University) have developed the Carbon Burnout Kinetic (CBK) model of pulverized coal combustion. This model is a key component of ongoing work sponsored by the Department of Energy Office of Fossil Energy, Pittsburgh Energy Technology Center.

Coal is a heterogeneous substance whose structure and properties are highly variable on the length scale of the particle sizes used in combustion systems and these variations can be important for global coal char combustion kinetics. Simple char oxidation models based on mean properties cannot predict low reactivities observed at high carbon conversion and hence are not suitable for describing carbon burnout in industrial boiler systems. The degree of carbon burnout is an important system operating parameter, affecting boiler efficiency, electrostatic precipitator operation, and the value of fly ash as a salable byproduct.

Recent work has employed a statistical description of coal properties to describe the char oxidation kinetics of a heterogeneous particle population. Figure 1 shows predicted and measured particle temperature distribution profiles based on a distribution of particle reactivities. The use of statistics can increase the time required to achieve high levels of burnout by as much as a factor of five over that predicted by mean kinetics.

Thermal annealing of the carbonaceous char matrix is another significant mechanism that is responsible for decreased char reactivity during combustion. Recent kinetic measurements on chars subject to rapid transient heat treatment (done in collaboration with Prof. Jon Gibbons, Imperial College, London) show a significant decrease in char reactivity with a concomitant increase in crystalline order.

The recent insights from laboratory experiments have been incorporated into the CBK, a coal-general formulation that is specifically designed to predict the total extent of carbon burnout and the carbon content of fly ash for prescribed temperature/oxygen profiles typical of pulverized coal combustion systems. The key features of this integrated model combine a single-film model of char oxidation with descriptions of statistical kinetics. statistical particle densities, the decrease in particle reactivity due to thermal annealing, and the inhibition of oxidation in the late stages of combustion due to the presence of ashforming mineral matter in the particle.

Figure 2 shows a comparison of measured carbon conversion profiles with predictions of both a previously developed, char oxidation model using mean or global reaction kinetics and the CBK model. The new model successfully predicts the long times needed to reach high carbon conversions under practical combustion

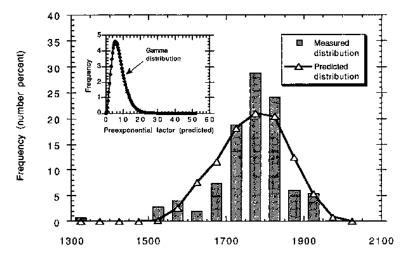


Figure 1. Measured and predicted particle temperature distributions for Pocahontas #3 coal char. Combustion conditions are 12 mole-% oxygen and a gas temperature of 1645 K. Inset is the gamma distribution of preexponential factors upon which the statistical predictions are based.

conditions. The CBK model is currently being implemented in commercial multi-dimensional codes used for furnace simulation (with Reaction Engineering International) and in stand-alone programs for carbon burnout prediction at EPRI-member utilities.

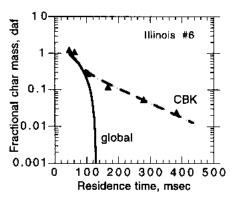


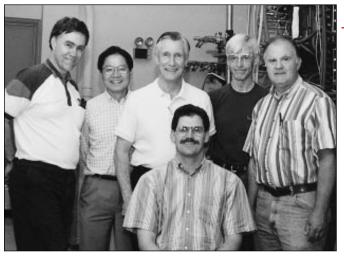
Figure 2. Comparison of measured conversion profiles from a one-dimensional laboratory reactor for Illinois #6 coal (points) with predictions of the simple, global char oxidation model using mean properties (solid curve) and the CBK model (dashed curve).

CRF on the Web

Be sure to check "What's HOT at the CRF," which changes monthly, at http://www.ca.sandia.gov/CRF/; previous "What's HOT" articles are viewable, too.

Also on the Web, the *CRF News* is available as a PDF file, readable with Adobe Acrobat; previous issues are archived under Publications. We are now offering a subscription service for Web users; see the *CRF News* page.

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Members of the Petroleum Environmental Research Forum visited the Burner Engineering Research Laboratory for a penultimate toxic sampling session in May. From left: Al Verstuyft (Chevron), Harry Tang (Shell), Jim Seebold (Chevron), Neal Fornaciari (seated), Pete Walsh, and Lloyd Claytor.



Marco Krumbügel, Berlin, Germany, (right) has been a Humboldt Fellow working with Rick Trebino on ultra-short laser pulse measurement using frequency-resolved optical gating (FROG) and an artificial neural network.



Christoph Espey, now with Mercedes Benz, returned to the CRF for the month of August to work with John Dec on the Sandia/Cummins heavy-duty diesel engine project. They conducted a study of the diesel autoignition process using a chemiluminescence imaging technique that they developed two years ago while Chris was conducting his Ph.D. dissertation research at the CRF (see *CRF News*, **15**:3 and **16**:2).



Post Doc Quang-Viet Nguyen (right) and Phil Paul have been examining the behavior of flame-vortex interactions using planar laser-induced fluorescence (PLIF) techniques (see article on front page).



Helle Junker (right), an employee of Elsamprojekt (a Danish utility-affiliated company) spent five months investigating combustion of coal and biomass blends with Larry Baxter in the Multifuel Combustor Laboratory.

TNF workshop held

The International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames (TNF) was held in Naples, Italy on July 26-27, 1996 preceding the 26th International Symposium on Combustion. Organized by Rob Barlow in collaboration with several researchers in the international combustion community, this workshop attracted 61 participants from 11 countries. The objectives were to identify a set of well documented experimental flames and to define guidelines for collaborative comparisons of model predictions of these flames. Information about this ongoing process is available on the Web:

http://www.ca.sandia.gov/tdf/Workshop.html

Transient response of premixed flames

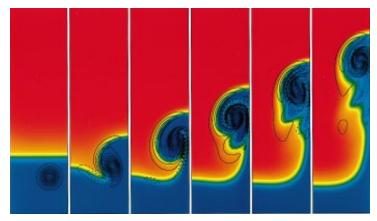
Combustion systems rely on turbulence and large-scale flow unsteadiness to provide sufficient mixing and flame stabilization, in order to ensure stable, efficient, and clean combustion. The resulting reacting flow involves significant interaction between unsteady flow dynamics and chemistry. The associated transient flame response dictates the incidence of flame extinction, pocket formation, and pollutant generation in these flows. To investigate these issues, Habib Najm and Peter Wyckoff have recently studied unsteady flame response in a flow involving the interaction of a premixed methane-air flame with a two-dimensional counter-rotating vortex pair, using detailed chemical kinetics and a low Mach number reacting flow model.

Flow dynamics are illustrated in the figure, which shows the evolution of the vortex pair and associated flame contortion. Counter-rotating poles of baroclinic vorticity are generated due to prevalent pressure and density gradients and are entrained into the vortex pair, which propagates into the flame, creating a pocket, and a trailing channel, of reactants.

At the flame location on the vortex-pair centerline, the flow-induced tangential strain-rate is observed to be in excess of the steady-state extinction value. The present flame continues to burn under these conditions, however, while tending towards extinction. This is because of its inherent time constant, on the order of 1 ms, that determines its response time to external disturbances.

Analysis of the flame structure at the centerline illustrates the process by which the flame is driven to extinction by the vortex pair. The reaction zone is observed to shift into the hot products, leading to significant reversal of the radical-producing reactions, along with reduction of available $\rm O_2$ and associated chain-branching reaction rates. The resulting depletion of active radicals H, O, and OH drives the flame towards extinction.

Diffusional disturbances are dominant at the curved flame cusp, leading to modification of the internal flame structure and reaction rates. Results indicate the significant effect of



Premixed methane-air flame interaction with a counter-rotating vortex pair. The right-hand edge of each frame is the centerline of the vortex pair, only half of which is shown. Each frame size is $0.4\,\mathrm{x}$ 1.4 cm, and the time interval between adjacent frames is $0.2\,\mathrm{ms}$. The color map indicates gas temperature, with the unburnt mixture of methane and air at room temperature in blue, and the burnt combustion products at $1600^{\circ}\mathrm{C}$ in red. The flame location is where the rapid color transition is observed. The solid/dashed contours delineate levels of positive/negative vorticity, where positive vorticity corresponds to counter-clockwise fluid rotation.

flame curvature on the diffusional fluxes of H and its precursors internal to the flame, which leads to both enhanced H-production *and* reduced CH_4 consumption at the cusp.

This work continues to involve comparisons with the flame/vortex-pair interaction experiment of Phil Paul, and is being extended to include C $_2$ compounds and NO_{x} chemistry. This will enable the study of unsteady NO_{x} generation and investigation of the observed transient OH dynamics of rich flames.

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